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First Validation of the Haptic Sandwich: A Shape Changing Handheld Haptic Navigation Aid

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Abstract— This paper presents the Haptic Sandwich, a handheld robotic device that designed to provide pedestrian navigation instructions through a novel shape changing modality. The device resembles a cube with an articulated upper half that is able to rotate and translate (extend) relative to the bottom half, which is grounded in the user's hand when the device is held. The poses assumed by the device simultaneously correspond to heading and proximity to a navigational target. The Haptic Sandwich provides an alternative to screen and/or audio based pedestrian navigation technologies for both visually impaired and sighted users. Unlike other robotic or haptic navigational solutions, the haptic sandwich is discrete in terms of form and sensory stimulus. Due to the novel and unexplored nature of shape changing interfaces, two user studies were undertaken to validate the concept and device. In the first experiment, stationary participants attempted to identify poses assumed by the device, which was hidden from view. In the second experiment, participants attempted to locate a sequence of invisible navigational targets while walking with the device. Of 1080 pose presentations to 10 individuals in experiment one, 80% were correctly identified and 17.5% had the minimal possible error. Multi-DOF errors accounted for only 1.1% of all answers. The role of simultaneous or independent actuator motion on final shape perception was tested with no significant performance difference. The rotation and extension DOF had significantly different perception accuracy. In the second experiment, participants demonstrated good navigational ability with the device after minimal training and were able to locate all presented targets. Mean motion efficiency of the participants was between 32%-56%. Participants made use of both DOF.

Keywords— *Haptics and Haptic Interfaces, Physical Human-Robot Interaction, Personal Robots, Human Centered Robotics, Assistive Technology*

I. INTRODUCTION

GPS technology and smartphone devices have made technology-assisted outdoor navigation commonplace for pedestrians. More recently, indoor localization and navigation is being commercially offered by such companies as Stick'n'Find, Indoo.rs and various iBeacon vendors. Electronic mediated navigation is finding application beyond typical pedestrian navigation scenarios (e.g. finding a specific restaurant in a city center or mall). GPS responsive audio guides and 'sound walks' are examples of linking user location to dramatic experience [1]. The immersive theatre installation 'The Question', explored the use of a handheld haptic

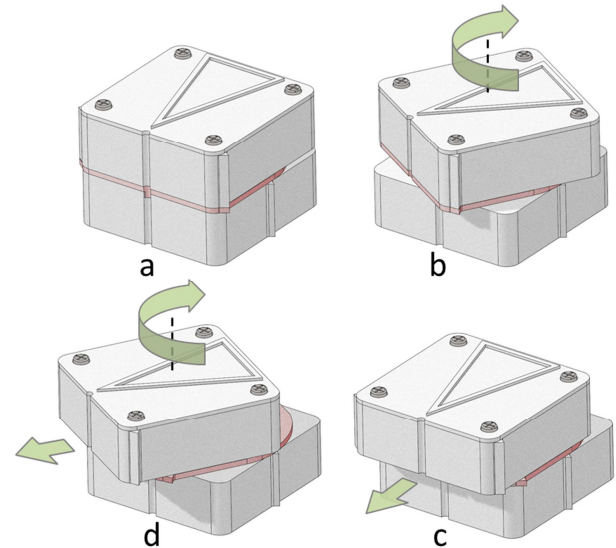


Fig 1: Shape changing in the haptic sandwich a) home b) rotation c) extension d) rotation and extension

navigation device (*The Haptic Lotus*) in a pitch black environment as a form of sensory augmentation [2]. This was to investigate the potential for equivalent cultural experiences between sighted and visually impaired individuals. The work described in this paper is partly an extension of that exploratory work. A common aim is to develop highly intuitive haptic navigation interfaces for a variety of users and applications with tests both in the laboratory and 'in-the-wild'.

A primary user interface of typical navigation technology is via screen-based maps and visual instructions. This has been described as surprising by the authors of [3], who consider walking to be an activity that requires visual attention to the environment, rather than a screen. In line with this, reviews of hospital reports have highlighted an increasing number of pedestrian mobile phone related injuries from 2005 to the 2013, as cellular phone usage becomes more ubiquitous [4]. A common alternative method of navigational instruction is via audio cues, which are often used in automobile navigation or by visually impaired (VI) pedestrians. For the latter, such audio cues, particularly when delivered through headphones, can obscure or distract from sounds of the natural environment [5]. Such ambient sounds may be used for landmark recognition (e.g. a fountain), danger (an approaching vehicle) or simply social interaction and the appreciation of one's surroundings.



Fig 2: The Haptic Sandwich device held in hand

Karcher et al. proposed that a device that could provide spatial information without drawing on attentional resources could greatly enhance the lives of blind travelers [5]. The use of appropriate haptic sensations for navigation could therefore reduce attention demands for both sighted and visually impaired individuals. Interest in the recently announced Apple Watch illustrates the widespread potential of such technology. The Apple Watch features a non-vibratory haptic interface that may be used to provide navigation instructions (‘turn by turn directions’) without the need for visual or auditory attention (<https://www.apple.com/watch>).

According to [6], vibrotactile feedback has dominated haptic guidance research, primarily due to ease of technical integration. More typically, this modality is used to provide attention grabbing alerts in mobile phones [5][6]. Such constant alerts may not be appropriate to navigation, particularly over extended periods of time. There exist a wealth of alternative haptic sensations that may be used not just to convey alerts but to elicit alternative, discrete and more natural stimulus [6]. Motivated by this, the authors developed a device deemed the *Haptic Sandwich* (Fig 1, Fig 2) to explore an alternative form of touch based feedback for navigation.

The haptic sandwich provides a handheld shape-changing interface, capable of providing two axes of navigation information simultaneously via rotation and radial translation of the upper half of the device body. By holding the device as it actuates to different ‘poses’, a user is able to feel and interpret instructions through natural exploratory procedures related to object shape [9][10]. The device was nicknamed the haptic sandwich due to construction analogies with a sandwich. It has matching square top and bottom sections (the ‘bread’) which sandwich the transmissions and actuators (the ‘filling’).

II. RELATED WORK

The use of robotic devices for visually impaired navigation has often been proposed (see [11][12] for examples), however these robots are often large, cumbersome and expensive. Wearable technology solutions are also common (see [13] for a review) but are also often ungainly or restrict motion and clothing options (e.g. the act of putting on or removing a jacket would confound many of the systems in [13]). It is likely that

such practical factors have limited the success of such technologies beyond the laboratory.

The use of ‘natural’ haptic sensations for navigation assistance is commonplace. Guide dogs and white canes both provide haptic guidance cues via a VI user’s hand. Numerous prototype haptic devices have addressed guidance assistance via vibration feedback [6][14]. A notable example device being the *FeelSpace* belt, which implemented a ring of vibrotactile actuators pressed against the user’s waist [15]. By persistent vibration of the most north facing actuator, the system investigated effects of sensory augmentation on the wearer. This was reported, after several weeks, to reduce walking path length in familiar environments and increase feelings of security for a blind individual [5]. Other study participants however reported the constant vibrotactile stimulus as being “annoying” and impairing concentration [16]. These reports are supported by [7] where the alerting nature of vibrotactile feedback applied to non-critical tasks (posture guidance) is argued to be potentially distracting from more important tasks (typing). As such, the authors argue for greater appreciation of user’s *attention spectrum* when designing haptic interfaces. This is particularly true when considering the attention requirements of pedestrians, discussed in Section 1.

Beyond vibrotactile, there are various interface methods for ungrounded haptic communication. Skin stretch factors have conveyed direction on the finger pad [17]. Spinning flywheels [18], miniature mass-spring-dampers [19] and moving weights [20] have all been used to generate ungrounded directional force effects. An unusual device, *Pull-Navi*, pulled the ears of a user in various directions to provide navigation guidance [21]. Though a number of the cited approaches have demonstrated promising results, Hemmert et. al. [3] show concern over social acceptance issues. For example, the constant buzzing sound of the *FeelSpace* tactors or large head-mounted hardware of *Pull-Navi* [21] and *vOICE* [13] may draw unwanted attention to the user. For this, and reasons of general convenience, handheld devices which may be stowed when not in use are likely to be more realistic alternatives for daily use. The success of the guide cane and cellular phone are testament to this.

An alternative method of communication, which is the focus of this paper, is via shape changing interfaces. The appreciation of shape and volume within the hand is a fundamental haptic ability [10] which we, the authors, believe to be more naturally encountered than stimulation by vibration. It may therefore fall within a more appropriate region of the *attention spectrum* [7] for unobtrusive communication and guidance. Many shape changing devices are primarily input tools, with the user physically modifying the shape of the object (via pulling, squeezing etc.) to change its functionality [22]–[24]. A number of actuated systems are able to drive their own bodies, or parts of their bodies, into alternative forms in order to communicate visual or haptic concepts [25], [26]. A notable example here being 2DOF actuation of a mobile phone back plate in order to facilitate body tapering or thickness change for physical representation of digital data [3].

In this work we consider a prototype device that is able to modify the shape of its body to communicate navigational concepts. We define shape as the contours of the device body,

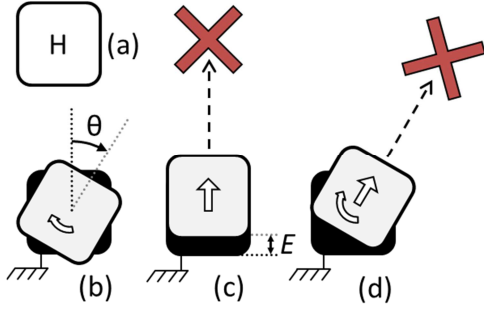


Fig 3: Navigation instructions a) home b) rotation c) extension d) rotation and extension

as perceived by a holder's sense of touch [10]. This is a continuation of the author's previous work on the *Haptic Lotus* handheld navigation device [2], which expanded as the user approached a target destination. This physical representation of proximity permitted a target to be found while also encouraging active exploration of the environment (the device was developed for the immersive art installation). In the Haptic Sandwich, proximity and direction may be physically represented via a device body that is capable of pointing to the target (rotating) and growing in length (extending) to illustrate distance magnitude. We believe these features may be felt simultaneously by a holder of the device, as their grasp on the device automatically directs them to the exploratory procedures facilitated in shape and volume identification (enclosure and contour following) [7][8]. Additional tactile body features (ridges and grooves) further enhance shape perception. Using the topological shape changing device classification of [26], this device can change both its form and orientation. Considering the static nature of the device after a pose (final shape) has been assumed, we believe this modality to sidestep the persistently stimulating, high attention signals of vibrotactile feedback, as identified by [4][5][10].

III. DEVICE DESIGN

Navigation with the haptic sandwich is based on simultaneous presentation of two types of spatial information, *position error* and *orientation error*. These two parameters relate to the current separation of an agent from their target location (or the next waypoint in a sequence of instructions). The haptic sandwich is designed to be vaguely cubic in shape, with rounded vertices for comfort and additional tactile markers to indicate the top and front of the device. The device is horizontally split into upper and lower sections with the top half able to rotate and extend relative to the bottom half. Kinematically, the device is equivalent to a classic Rotational-Prismatic (RP) serial robot with zero link lengths. The analogy to the RP robot is such that rotation angle indicates direction to a target, while prismatic extension indicates proximity to a target. Fig 3 provides some examples of how different device body poses relate to navigational cues. In (a) the device is at the 'home' position. There is no extension and the rotation angle is zero. The overall shape resembles a cube to indicate that the user is at their destination. In (b) the top half of the device rotates to indicate that the user should turn by θ degrees to face the navigational target. In (c) the device linearly extends proportional to the distance to the destination. In (d)

the user is instructed that the destination is at a given distance and heading. These motions are also presented in the 3D renderings of Fig 1 with the same alphabetical key.

Lessons learned from 'in the wild' testing of the Haptic Lotus [2] motivated the design of the Haptic Sandwich. In addition to providing navigation information in a compelling but unobtrusive way, the *Sandwich* has also been designed for robustness, ease of fabrication, comfort, aesthetics and low fabrication cost. Apart from bolts, threaded inserts, servomotors and spur gears, all elements of the haptic sandwich are 3D printed. Gear teeth for the linear and rotational transmissions are printed as features of the relevant parts of the device. Assembly requires only a screwdriver and takes 20 minutes. The cost to build a device is approximately \$75 (USD). This has enabled six devices to be easily assembled for a future navigation study involving over 50 participants.

To achieve the proposed user interface concept, the device was designed for articulation in multiple, distinct DOF while partially enclosed in an adult hand. After reviewing a number of actuators it was noted that many conventional solutions had incompatible volume demands. In particular we wished to avoid a wide or tall device, for which users with shorter fingers would not be able to enclose important features of the device body. Furthermore, a major observation of the Haptic Lotus during public use [2] was that many individuals would grip the device tightly, overpowering the actuation mechanism and significantly reducing their ability to feel the haptic sensations provided. The new device should therefore be able to exert sufficient forces to overcome tight grasps. By using miniature servos (metal gear HS-82MG) in a horizontal configuration with a 3D printed rack and crown gear transmissions, it was possible to reduce the device's height demands while increasing actuator torque and force output. The device dimensions are $60 \times 60 \times 45$ mm (L \times W \times H). It weighs 105g. The force / torque exertion capability is 25N for the linear actuator and 1Nm for the rotational actuator. Power and control are currently provided externally, but space has been left inside the upper and lower sections to accommodate a wireless embedded controller and miniature Lithium Polymer battery pack.

A 32 pitch linear rack gear 3D printed into the top half of the device engages with an acetyl spur gear (13 teeth, 12.06mm OD) directly mounted onto the servo output spline. The servo is mounted sideways (to reduce device height) on a central plate featuring linear guide rails. A servo holder component holds the half of the device together with two M2 bolts. A top plate with a raised triangle tactile feature (to aid orientation of the device when initially picked up if unseen) covers the mechanism. Fig 4 illustrates this assembly. The transmission provides 12.5mm of linear actuation from servo's range of motion (illustrated in Fig 1c and Fig 1c d).

In the bottom half of the device a second servo motor with a larger acetyl spur gear (22 teeth, OD = 19.22mm) interfaces with a 32 pitch crown gear 3D printed onto the underside of the central plate. Guide rails and a central bolt enable rotation of the central plate relative to the bottom section, following movement of the spur gear (Fig 5). A bottom plate covers the mechanism and secures the servo in place. The transmission

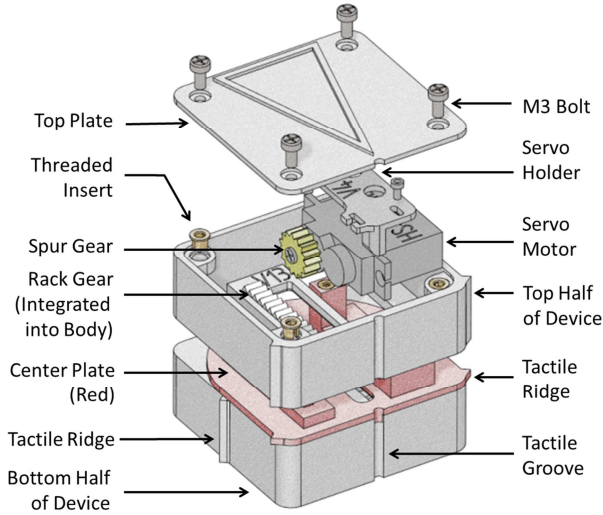


Fig 4: Exploded view of the extension actuator

affords $\pm 30^\circ$ of rotation via a 1:3 gear reduction from the servo output ($\pm 90^\circ$).

A housing feature on the underside of the device holds an optional vibration motor. This can provide complementary haptic information, such as an alert that the device is being held incorrectly. This was not included in the presented studies.

On the bottom half of the device, tactile ridges on the side faces provide a reference to enhance rotation perception (Fig 5, Fig 1). On the center plate and top half of the device, ridges towards the front align when the device is closed and separate as extension increases (Fig 4, Fig 1). A vertical ‘tactile groove’ (Fig 4, Fig 1) aligns on the front face of the major sections when the rotation angle is zero (Fig 3).

IV. EXPERIMENT ONE – PERCEPTION

The goal of the haptic sandwich device is to present navigational information via an unobtrusive touch based sensation. These instructions should be easy to understand and clearly discernable. Sensitivity of the human body to common haptic feedback modalities and static shapes has been established through various studies (e.g. [9][27]). However, test data is limited for shape changing modalities, particularly due to the scarcity of such systems. Due to the novel nature of the haptic sandwich, it was unknown whether instructions provided via the variable-shape modality could be perceived and interpreted. Questions also arose as to whether shape perception was influenced by the transient movement of the system between poses (for which many trajectory options exist), or just the final resting shape. Expanding on these ideas, the following questions were addressed by the first experiment:

- How accurately can individuals feel the different poses (shapes) assumed by the device?
- Is device pose perception affected by the transition between poses (the kinematic motion trajectory)?
- Are some poses more difficult to perceive than others?
- Is one DOF more difficult to perceive than the other?
- Do larger hands / longer finger improve pose perception?

The first experiment therefore aimed to investigate and establish perception accuracy regarding the shape changing

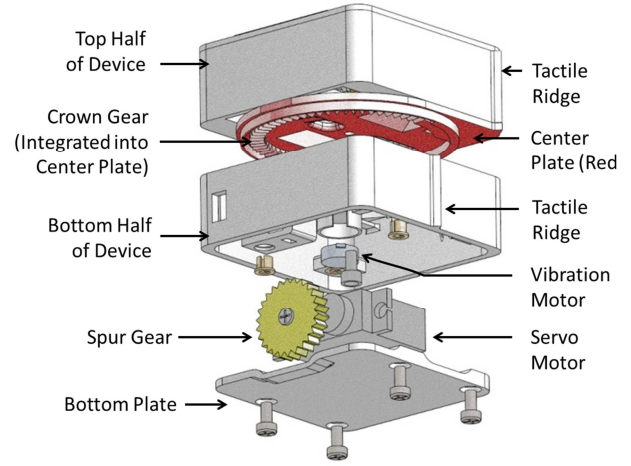


Fig 5: Exploded view of rotation actuator

interface. This was conducted as a proof-of-concept prior to conducting a full navigation study (which will be presented in Section II). Despite the navigational goals of the device, participants remained stationary for this initial study. We believe this significantly reduced the numerous variables present in a full navigation setup, where the continuous movements of the device and participants would make stimulus perception difficult to isolate. The experimental protocol was reviewed and approved by the Yale University Human Subjects Committee, HSC Protocol number #1407014391.

The experiment involved participants sitting at a desk with the device held in their dominant hand. The hand and device were hidden from view by an opaque box. The inside of the box was lined with soft padding and an adjustable arm rest is provided to increase participant comfort during the study. Participants were shown how to hold the device so that the front face was distally orientated the base maintained contact with the palm. Fingers and thumb were lightly wrapped around the device (Fig 2). Participants were instructed that during the study they are free to explore the device with their fingers but should maintain palm contact with the device base and a palm upwards hand pose. In front of the participant is a computer monitor showing a top down chart which illustrates 28 poses of the device (Fig 6). Though the device is able to move continuously through its workspace, precise discrete poses were selected for the study. This was to allow ease of participant input selection and subsequent data evaluation. The poses are based on 4 equally spaced extension values (0, 4.15, 8.3, 12.45mm) and 4 rotation values (0, 10, 20, 30deg). Rotation was presented in both clockwise and anticlockwise directions across the horizontal chart axis. Extension related to the vertical axis. To maintain accuracy between the visual chart and device, the chart was generated from the CAD files used for component fabrication. The chart is presented as part of an application written in the language *Processing*. The application also controls the actuators of the haptic device (via an *Arduino Uno*) and logs participant responses.

During the experiment the haptic device moves from the home position (Fig 1(a), Fig 2, Fig 3(a)) into a randomly ordered pose. Once it has achieved a pose, a red rectangular cursor appears on the chart (Fig 6). The participant then uses

arrow and enter keys on a numeric pad (with their non-dominant hand) to direct the cursor and select which pose they believe the device to be in. No participants complained of errors from using their non-dominant hand for this task. When a pose has been selected the device returns to the home position, pauses for one second and then moves to another pose. The home pose is not included as a target pose and is not selectable by participants. No time limit is imposed on participant responses.

The experiment consists of two trials, with different actuator motion profiles. In the *simultaneous* profile the extension and rotation actuators start moving simultaneously. In the *sequential* profile the rotation actuator starts moving after the extension actuator has reached its target position. Participants alternated between beginning the experiment with sequential or simultaneous motor patterns.

Each pose is presented twice during each study, leading to a total of 54 poses. Eight random sequences of these 54 poses were generated prior to the start of the experiment. When the study is started one of the sequences is randomly selected by the *Processing* application. A different sequence is selected for the second study. To prevent participants from using movement duration as an indicator of device pose (longer movements would imply greater distance from the home position), actuator velocity is randomly selected from a given range at the start of each new movement. The same velocity is applied to both actuators.

Prior to the start of each study, the participant undergoes training with the haptic device using the motion profile associated with that study. The device and user's hand are also hidden from view during training. Training involves using the same chart and cursor interface as the study, but after each pose selection a green cursor appears to illustrate the true pose of the device. The sequence of poses in training is pre-determined and consists of 24 poses. The first 16 poses are accompanied by verbal guidance from the experimenter and illustrate key poses in the chart (for example, all rotation and extension magnitudes independently, followed by several combined motions). The remaining 8 poses are pseudo random from equally distributed areas of the chart. Progression to the next pose is manually controlled by the experimenter to allow the participant time to explore the device with their fingers and ask questions. To negate learning bias effects, the second training sequence mirrors the first with respect to rotation direction.

V. EXPERIMENT ONE RESULTS AND DISCUSSION

10 participants (3 female, ages 22-31, all right handed) completed the experiment. Participants completed a screening questionnaire which asked about any impairment to their dominant hand (current or past) that may affect their ability to comfortably hold, explore or feel the device. No impairments were reported. In total 1080 pose selections were recorded, this involved 540 recordings for each motion profile and 40 recordings for each of the 27 poses.

Results were scored on several criteria based around *pose selection accuracy*. This was determined by the Euclidean distance between the user's pose choice and actual pose in the

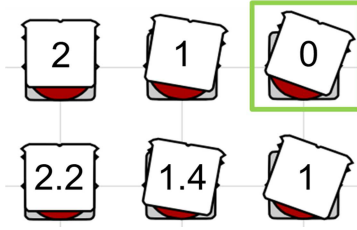


Fig 7: Euclidean distance based error scores for pose choices. The correct score is highlighted by the green square.

selection chart, giving an error value. For example, if the actual pose was horizontally or vertically adjacent to the user's choice on the chart then the error score would be 1 (square), which is the smallest possible error. The closest diagonal error would generate the Euclidean error score of 1.4. Example error scores are illustrated in Fig 7.

Two tail t-test comparison of participant error scores for the different movement types showed no significant ($p < 0.05$) difference in pose accuracy between simultaneous vs sequential motor movements ($p = 0.720$). The mean sum of error scores for the simultaneous study was 14.42, while the sequential motion study produced a score of 12.85. Distribution of pose errors selections are shown in Table 1 for the two motion profiles and total results. The error results are similar across all cases with less than 1% deviation between groups. Multi-DOF errors refer to misidentification of both extension and rotation. 79.55% of user choices featured no error, while 17.5% involved the minimum possible error.

To test whether certain poses are more difficult to identify than others, the average (cumulative mean) Euclidean error score for each pose was calculated across all trials. This was also calculated separately for horizontal and vertical components of the error calculation to investigate an accuracy bias between extension and rotation DOF. The results are presented in color scaled tables in Fig 8 where the cell distribution corresponds to the pose chart (Fig 6). Note that due to the cumulative nature of a mean average, only pose choices with errors (20.46% of all results) contributed to these values. The remaining 79.54% of choices contributed an error score of zero (Table 1).

The average error score is relatively small, with the highest error (square C3) being 0.53 units. Note that due to the few

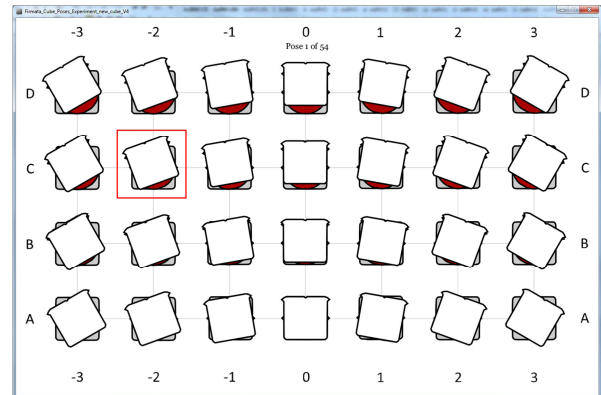


Fig 6: Pose chart presented to study participants

Table 1: Error magnitude distribution for pose choices

Error	Simultaneous	Sequential	Total
No Error	79.07%	80.00%	79.54%
1 Square	17.96%	17.00%	17.50%
>1 Square	2.96%	2.96%	2.96%
Multi-DOF	0.56%	1.67%	1.11%

Multi-DOF errors contributing to both rotation and extension error scores, the sum of the rotation and extension matrices in Fig 8 do not equate to the total score. This analysis was also undertaken for the different movement types but cannot be presented due to limited space. Similar trends were observed. Fig 8 illustrates that the extension DOF was more commonly misinterpreted than the rotation DOF. Extension perception accuracy decreases with rotation magnitude. This is also true in the opposite case, where increased extension reduces rotation perception. The DOF appear easier to distinguish when not coupled.

Two tailed t-test comparison of participant rotation (horizontal) vs extension (vertical) error scores for showed significant differences in simultaneous ($p = 0.002$) but not sequential ($p=0.134$) movement trials. In an analysis of all trials (simultaneous + sequential), participant rotation vs. extension error scores are shown to be significant ($p=0.002$). The mean average extension based error scores across all trials is 10.25 compared to 3.65 for rotation, implying that extension is more difficult to perceive than rotation. Recall however that all these errors account for only 20% of all trials.

The charts are non-symmetrical which is believed to be due to the non-symmetrical nature of the human hand. As all participants were right handed one may assume that it is more difficult to perceive rotation and extensions in the region of the thumb than in the region of the little finger. Dominant hand size was measured by the length of the index finger, middle fingers and palm width at the widest point. Three individuals had much smaller hand sizes than other participants (mean of

Total Mean Error Score							
0.37	0.33	0.25	0.08	0.34	0.48	0.43	
0.37	0.24	0.35	0.08	0.37	0.43	0.53	
0.21	0.25	0.14	0.08	0.11	0.18	0.41	
0.11	0.26	0.00	H	0.03	0.16	0.50	
Rotation Mean Error Score							
0.16	0.11	0.08	0.08	0.11	0.24	0.13	
0.16	0.08	0.08	0.08	0.11	0.11	0.08	
0.03	0.05	0.08	0.03	0.05	0.03	0.03	
0.00	0.03	0.00	H	0.00	0.00	0.00	
Extension Mean Error Score							
0.24	0.26	0.18	0.00	0.26	0.37	0.39	
0.16	0.21	0.26	0.00	0.29	0.34	0.42	
0.16	0.21	0.11	0.05	0.05	0.13	0.34	
0.08	0.24	0.00	H	0.03	0.16	0.37	

Fig 8: Average Euclidean error score per pose. Cell arrangement corresponds to the pose chart (Fig 6)

measurements < 22mm and sum of measurements < 75mm). Two tailed t-test comparison of error scores for these participants showed no significant differences compared to the larger hand size groups with regard to simultaneous ($p=0.349$), sequential ($p=0.990$) or combined results ($p=0.212$).

The results are encouraging, indicating the device is able to provide clear instructions to participants with a variety of hand sizes. Both motion profiles produced similar, low error scores. The simultaneous presentation of data is considered less likely to constrain individual's navigation techniques so was selected for use in experiment two, which follows.

VI. EXPERIMENT TWO - NAVIGATION

Following the verification that individuals are able to adequately perceive shapes assumed by the robot, a second study was completed to test the ability of participants to practically follow navigation instructions from the device. A separate review approval was conducted by the Yale Human Subjects Committee, HSC Protocol number #1408014462. The study involved sighted participants locating a sequence of ten invisible virtual targets in an indoor environment.

A. Navigation System

To enable the haptic sandwich to provide guidance information, the position and planar orientation (heading) of the user with respect to a navigational target must be known. An indoor localization system was established using separate position and heading sensing components. This system is proposed as a proof-of-concept method that may be later replaced by more commonly available technology, such as GPS detected by a smartphone with an integrated IMU.

The position of the user is detected via a Ubisense Real Time Localization System (RTLS), consisting of 4 sensors mounted in the corners of a 5.1×5.3 m workspace. The sensors detect the position of wireless *UbiTags* via ultra-wideband (UWB) radio signals. Though limited to a maximum 15cm resolution, the Ubisense system is scalable to much larger indoor and outdoor environments, which suit the longer term requirements of these investigations. For example, a multi-user study in a darkened $30\text{m} \times 145\text{m}$ space is currently in preparation. Though placing the Ubitag on or near the handheld haptic devices would have been preferable, fastening the Ubitag to the top of a hat provided optimum localization results by avoiding occlusion by the user's body, which interferes with the UWB signals. These occlusion issues are less prominent in larger environments or with higher sensor mounting. Planar orientation of the user was measured via an *Adafruit 9DOF IMU*, and tilt-compensated magnetometer algorithm. The IMU was sewn to a Velcro strap and worn like a wrist watch on the user's dominant arm (which also held the haptic device as in experiment one).

The IMU and sandwich servos are connected to an *X-OSC* micro-controller with integrated Wi-Fi adapter. This is carried in a belt pouch, with *LiPo* batteries. A Windows PC, running custom navigation software communicates with the *X-OSC* via a Wi-Fi router. The navigation software (written in *Processing*) receives current user position and orientation and computes proximity and orientation error to the next target. Corresponding servo signals, scaled to the maximum

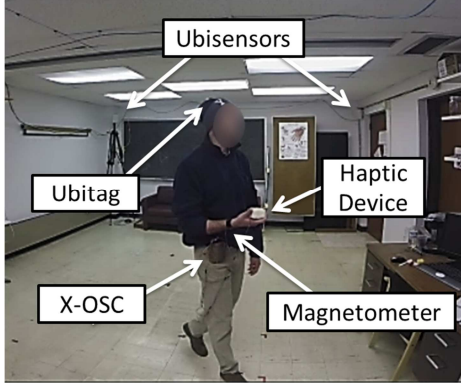


Fig 9: Experiment two familiarization conditions. The haptic device is covered with a cloth during the actual study

dimension of the workspace, are simultaneously transmitted to the *X-OSC*. Targets are pre-determined series of planar coordinates in the navigation software. The experimental setup may be observed in Fig 9 and Fig 10. Data recorded from static *UbiTags* demonstrated continuous position fluctuations by up to 0.32m. To account for this uncertainty, targets were established as circular areas with a 0.4m radius. Position data was low-pass filtered by the navigation software, to prevent actuator jitter. The navigation system updates at 100Hz.

B. Method

Participants were requested to use the haptic device to locate ten sequentially presented targets, after starting from a location marked on the floor. The targets were explained to the users as ‘invisible circular regions on the floor of the room’. As this study focused on general navigation ability, participants were not blindfolded and the room was well lit. Targets were considered ‘found’ when a participant remained inside the target radius for 2 seconds. This was to prevent the accidental ‘finding’ of targets by users who may momentarily pass through them during stochastic exploration. Once a target was registered as ‘found’, the device directed the user to the next target in the sequence. Participants were instructed to attempt to find the targets efficiently and at a comfortable walking pace, rather than attempting to locate them as quickly as possible. Prior to the study, participants underwent a brief familiarization process. This began with demonstration of the range of motion & haptic sensation of the device, while held by the participant. Following this, participants were requested to locate three sequential ‘training targets’ in the workspace. During familiarization the device was not visually obscured, so that participants were able to validate haptic sensations with visual observation of the device motion. Participants were free to ask questions of the experimenter during training. Training took less than 10 minutes in all cases. During the study the device was visually obscured with black fabric draped over the user’s arm and help in place with a stationary clip. Motion of the device could not be observed by motion of the fabric.

VII. NAVIGATION EXPERIMENT RESULTS

As this was an initial pilot experiment to validate fundamental navigation capacity of the system, a limited number of 3 participants (all male, ages 27-30) completed the study. A more in depth experiment is under preparation, which

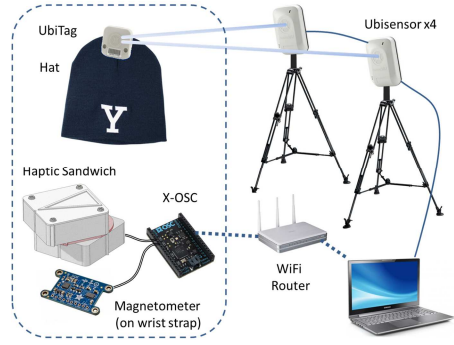


Fig 10: Localization system used experiment two. Sections in the dotted line are worn or carried by the user.

will examine the subtleties of the navigation technique with a larger group of participants. Of the three participants (P1-P3), only P1 had taken part in experiment one. The other two were previously unfamiliar with the device.

All participants were able to successfully locate all targets in the space. Navigational ability was primarily evaluated by the following *Path Efficiency (PE)* metric, which was applied separately to each of the paths between targets.

$$PE(\%) = \frac{E_p}{U_p}$$

Where E_p is the Euclidean distance between target (the optimal path), U_p is the distance covered by the user’s path and PE is the resulting path efficiency ratio. E_p considers the circular nature of the targets so measures distance from the circular target boundaries. A 50% path efficiency ratio would indicate the user had travelled twice as far as the straight line path between targets. Euclidean distances between the successive circular target boundaries (the edges of each target’s radii) ranged from 1.32m to 3.6m.

User path length (U_p) was calculated as the sum of Euclidean distances between successive positions (X_i, Y_i) and (X_{i+1}, Y_{i+1}) in the recorded Ubitag position log.

$$U_p = \sum_{i=0}^n \sqrt{|X_i - X_{i+1}|^2 + |Y_i - Y_{i+1}|^2}$$

Mean path efficiency for each participant was P1 = 56.4%, P2 = 42% and P3 = 32.3%. One P1 user path was removed from calculations due to a temporary *Ubisense* localization

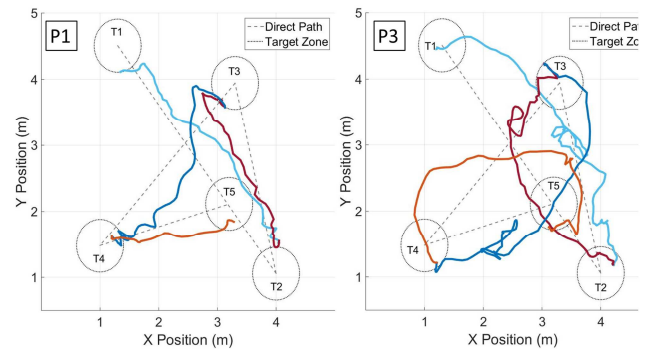


Fig 11: Example walking paths between 5 successive invisible targets (T1-T5) for participant one (P1) and three (P3)

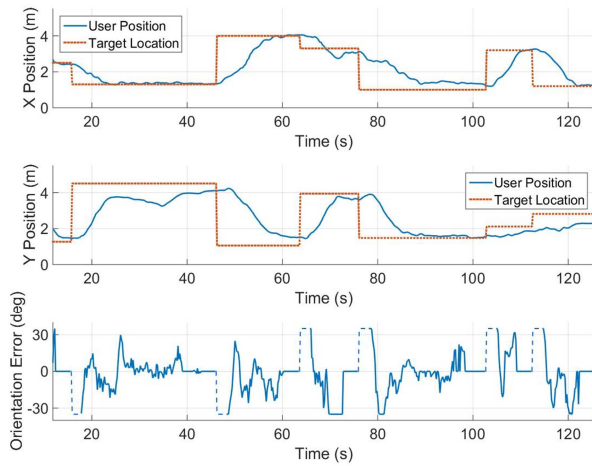


Fig 12: Log of Participant P1's X and Y positions (top and middle) with orientation error (bottom) for 7 targets.

error. User paths between targets T1 to T5 for participants P1 and P3 (the most and least efficient participants) have been illustrated in Fig 11. The remaining paths (T5-T10) have not been shown for benefit of image clarity. In both cases the paths show the user's correcting for travel in the incorrect direction. The concentrated oscillatory motions of P3 (for example between T3 and T4) occupy an area of less than 0.5m diameter so may be partly due to *Ubisense* localization jitter.

In Fig 12 the decomposed position and orientation error responses for P1 are presented for the paths T1 to T7. The participant exhibits a good 'tracking' behavior of the target positions, rarely changing direction or overshooting. Their orientation error is rarely outside of $\pm 35^\circ$, excluding when a new target is presented and the path is started facing the wrong direction (indicated by dashed lines). This indicates appropriate attention and response to the rotational DOF.

VIII. CONCLUSION

This paper has introduced a shape changing handheld robotic navigation concept and prototype, the haptic sandwich, which aims to provide unobtrusive and natural haptic sensations for navigation assistance. Initial user perception testing on the novel feedback modality of this device produced very promising results, with 97% of all participant responses either correctly identifying the device pose or selecting the adjacent pose (equivalent to 10° rotation error or 4.15mm extension error). This appeared adequate for conveying pedestrian navigation instructions so a pilot study was completed with 3 participants, who successfully located invisible targets with good efficiency.

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